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A two-year research effort on Navy applications of High-Tc SQUIDS is described. Over the course of the contract, we reviewed materials research and operation of SQUIDS in a small magnetic field. We examined some applications of SQUIDS, including Naval Gradiometers, Biomagnetometers and Scanning SQUID microscopes.

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High-Tc Superconducting Multilevel Materials and Device Development and Device Physics

Contract N00014-95-C-0056

PROBLEM TO SOLVE:
DEVELOP NAVY APPLICATIONS OF HIGH-TC SQUIDS

OUR PART OF SOLUTION:
UNSHIELDED/MOBILE OPERATION OF SQUIDS

Roger Koch
Frank Milliken
Jim Rozen
Steve Brown
Pieter Woeltgens

IBM Research
Yorktown Heights, NY

Review materials research

Review operation of SQUIDs in a small magnetic field

Examine some applications of SQUIDs
1. Naval Gradiometers
2. Biomagnetometers
3. Scanning SQUID microscopes

28 June 1999
Final Report Covering December 22, 1994 to December 21, 1996

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Prepared for:
Office of Naval Research
Department of the Navy
800 North Quincy Street
Arlington, VA 22217

SQUID APPLICATIONS:
Successful in a "*marketplace*":

1. Brain biomagnetometer
2. SQUID susceptometer
3. SQUID microscope
4. Scientific applications
5. Rock magnetometer

OPERATE WHILE SHIELDED AND/OR STATIONARY

Technically successful:

1. Geophysical sensors (e.g. MT)
2. Radiation receivers

OPERATE WHILE STATIONARY & "AWAY FROM IT ALL

Technically still very difficult:

1. Heart biomagnetometers
2. Navy submarine or mine detection
3. Most NDE applications

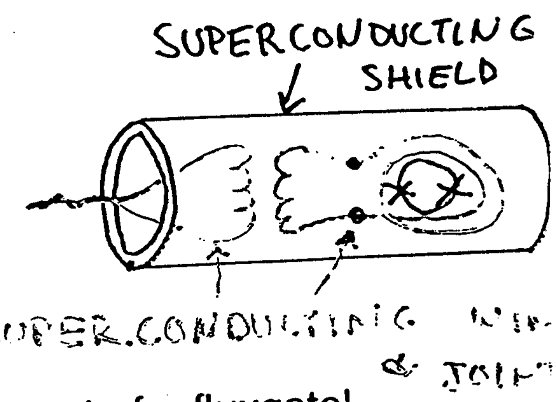
OPERATE WHILE/AFTER MOVING AND WHILE "POORLY" SHIELDED

USING SQUIDS IN UNSHIELDED ENVIROMENTS:

If High-Tc SQUIDs are to become economically viable products (that survive without government funding) we need to learn how to operate them outside of $B=0$, $\Delta B=0$, $\Delta T=0$, and RFI and magnetically shielded enclosures:

$B = B_{EARTH}$	use narrow lines and/or holes, fluxdams, heaters, laser zappers
$\Delta B \neq 0$	TSG active cancellation, fluxdams, good quality materials
$\Delta T \neq 0$	fluxdams, good quality materials
$RFI \neq 0$	high bandwidth electronics
Magnetic noise	magnetic references, gradiometers

OR DO WHAT IS DONE IN LOW-TC....
superconducting shields and wires

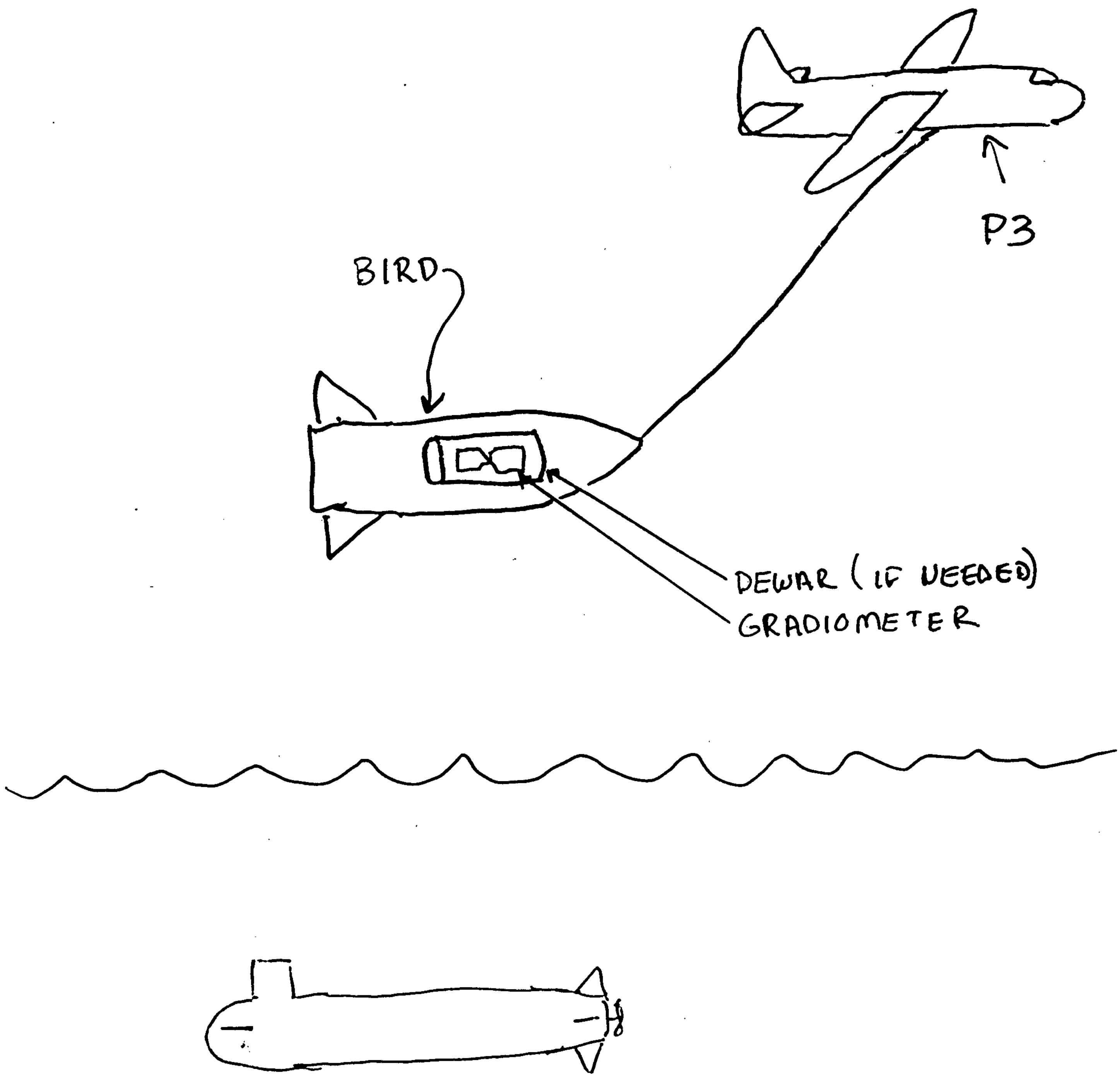


What we really need is the usability and cost of a fluxgate!

FLUXGATE → 2 pT/$\sqrt{Hz}$ @ 1 Hz — $ 1,000

HIGH-Tc SQUID 200 fT/$\sqrt{Hz}$ — $ 10,000

SUBMARINE DETECTION



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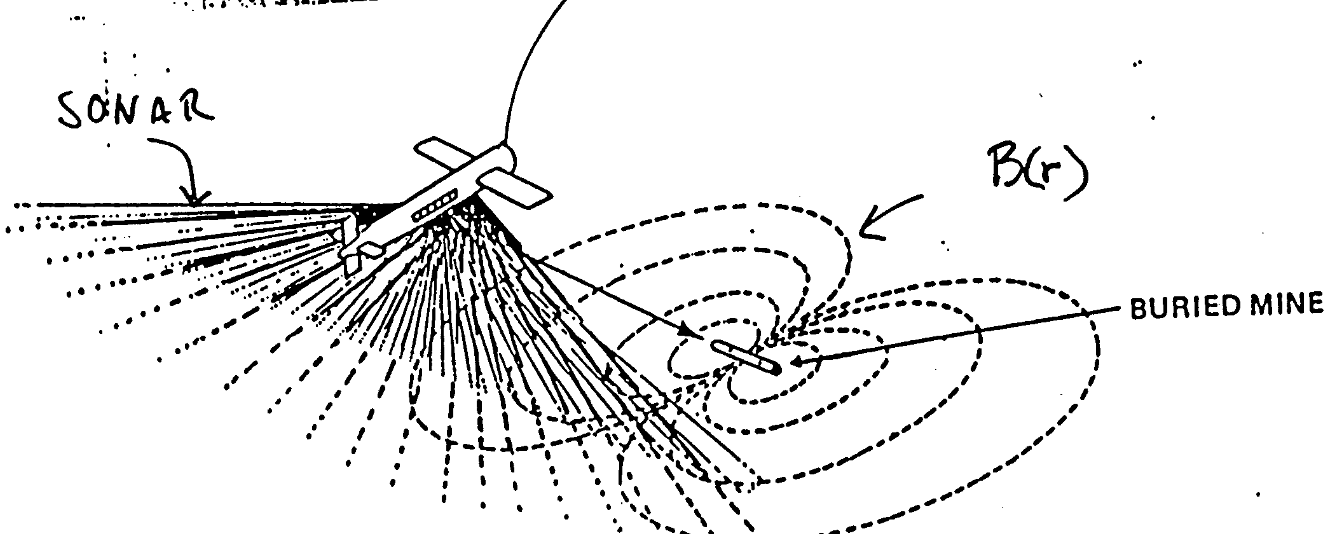
NCSC

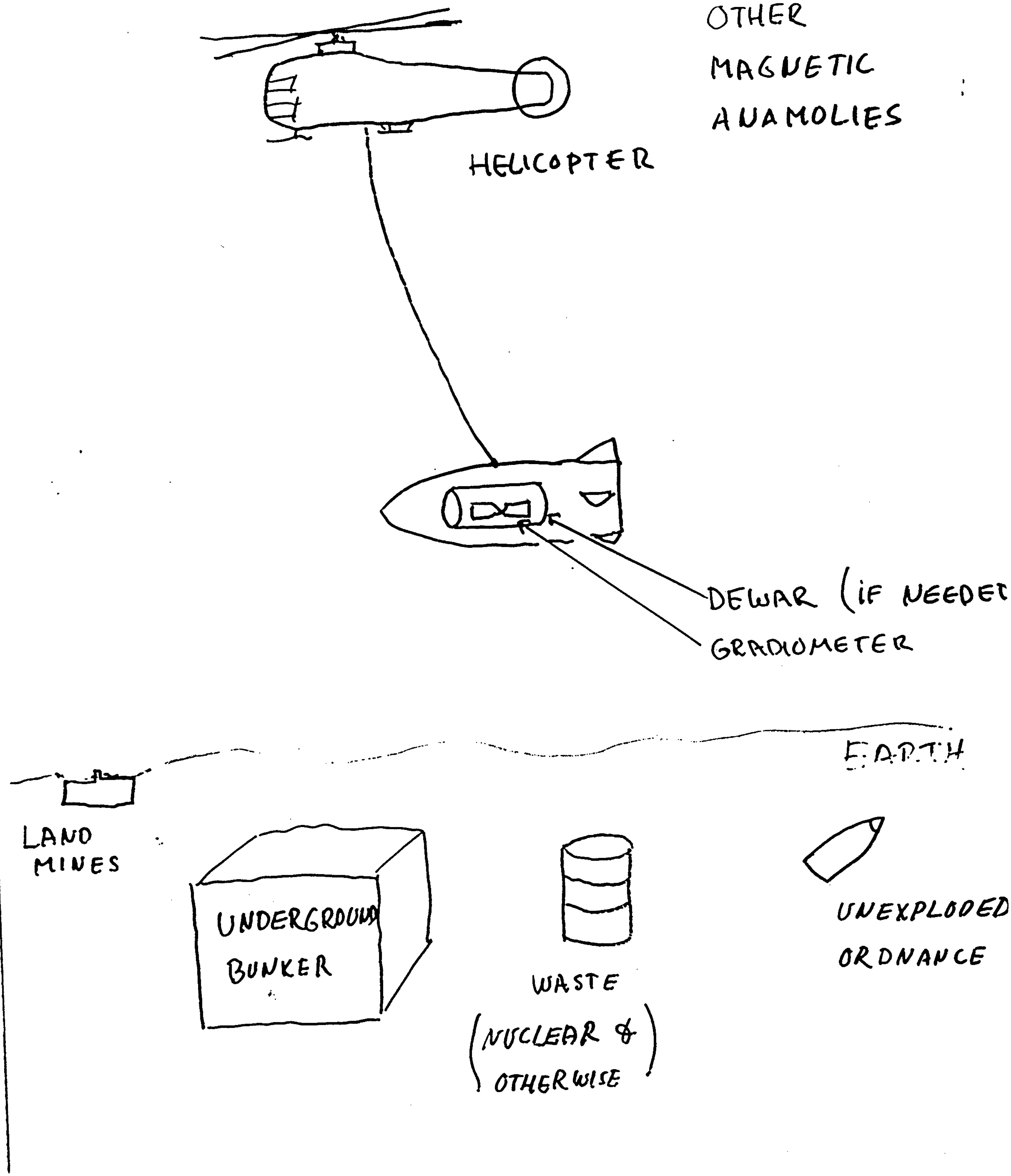
FUTURE MADOM CONCEPT



A SENSOR TRIAD WILL PROVIDE:

- HIGH DETECTION PROBABILITY
- LOW FALSE CONTACT RATE

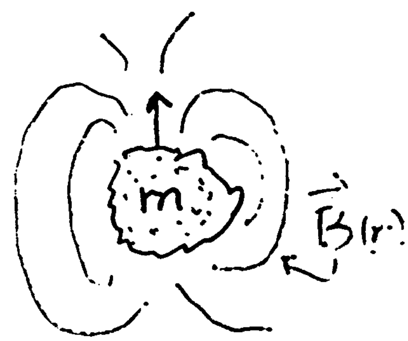
NAVAL COASTAL SYSTEMS CENTER—PANAMA CITY, FLORIDA


OTHER
MAGNETIC
ANAMOLIES
HELICOPTER
DEWAR (IF NEEDED
GRADIOMETER
EARTH
LAND
MINES
UNDERGROUND
BUNKER
WASTE
(NUCLEAR &
OTHERWISE)
UNEXPLODED
ORDNANCE

WHAT THE USER WANTS TO DO:

<u>FIND MAGNETIC ANOMALIES</u>

M.A.D. $\equiv$ MAGNETIC ANOMALY DETECTION



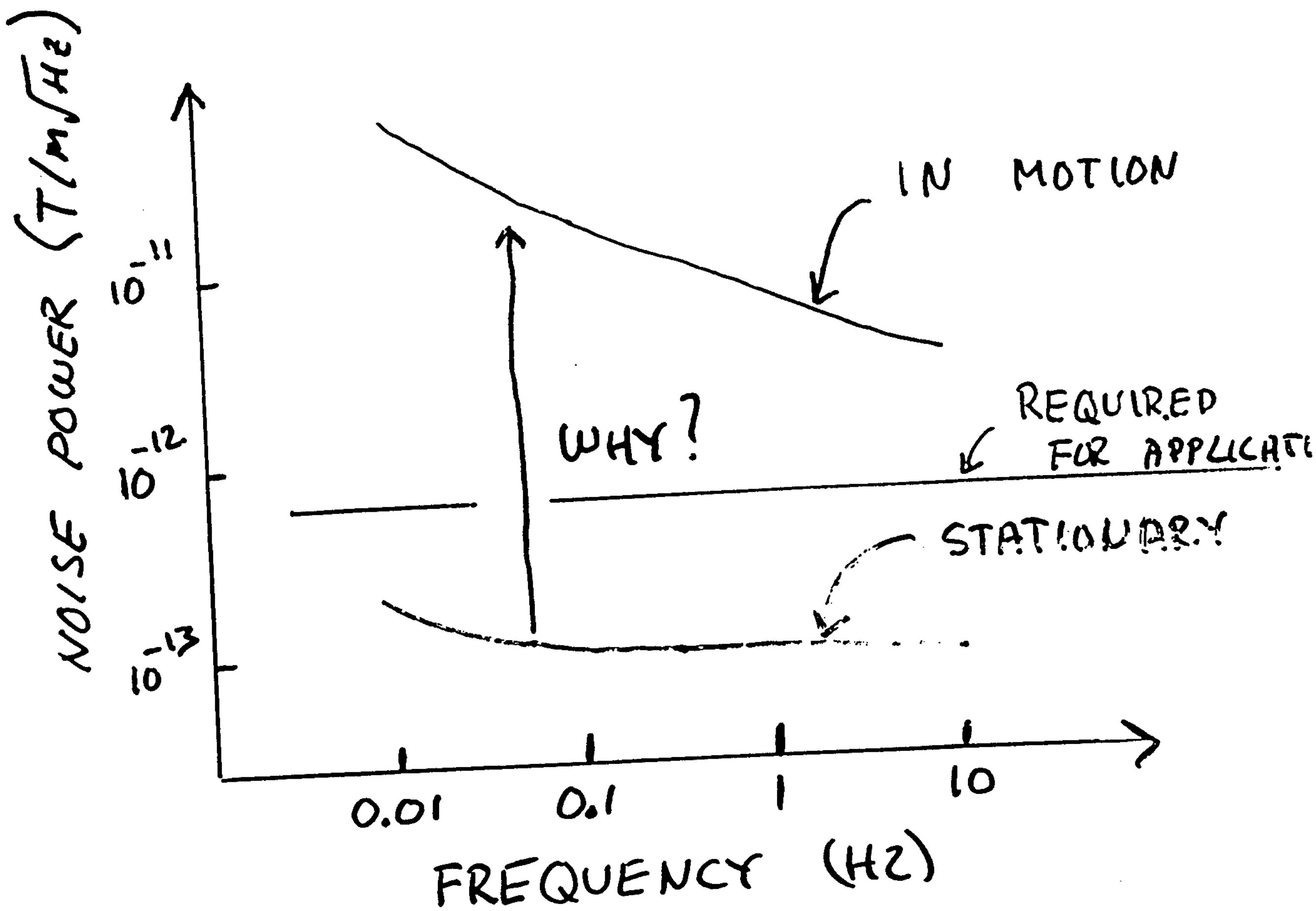
WHAT TO MEASURE ?

$$\left.\begin{array}{l}\text{1000 +}\\ \text{SYSTEMS IN}\\ \text{USE TODAY}\end{array}\right\}\ |B|\ \left\{\begin{array}{l}\text{EASY TO MEASURE}\\ \text{HARD TO INTERPRET}\end{array}\right.$$

$$\left.\begin{array}{l}\text{NONE}\\ \text{IN USE}\\ \text{TODAY}\end{array}\right\}\ \vec{B} \equiv [B_x, B_y, B_z]\ \left\{\begin{array}{l}\text{IMPOSSIBLE TO}\\ \text{MEASURE ON A}\\ \text{MOVING PLATFORM}\end{array}\right.$$

$$\left.\begin{array}{l}\text{20 YEARS}\\ \text{OF}\\ \text{RESEARCH}\end{array}\right\}\ \frac{d\vec{B}}{d\vec{r}} \equiv \begin{bmatrix} \frac{dB_x}{dx} & \frac{dB_y}{dx} & \frac{dB_z}{dx} \\ \frac{dB_x}{dy} & \frac{dB_y}{dy} & \frac{dB_z}{dy} \\ \frac{dB_x}{dz} & \frac{dB_y}{dz} & \frac{dB_z}{dz} \end{bmatrix}\ \left\{\begin{array}{l}\text{HARD TO}\\ \text{MEASURE}\\ \\ \text{EASY TO}\\ \text{INTERPRET}\end{array}\right.$$

MOTION INDUCED NOISE



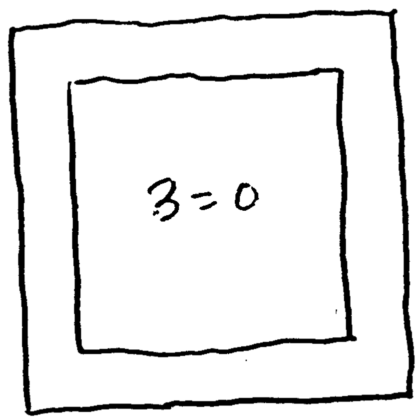
WHY THE INCREASE IN NOISE WHEN IN MOTION?

BIG PROBLEM FACING THE APPLICATION

LOW FREQUENCY NOISE (1/f) IN A MAGNETIC FIELD:

ZERO FIELD-COOLED

IN ZERO FIELD



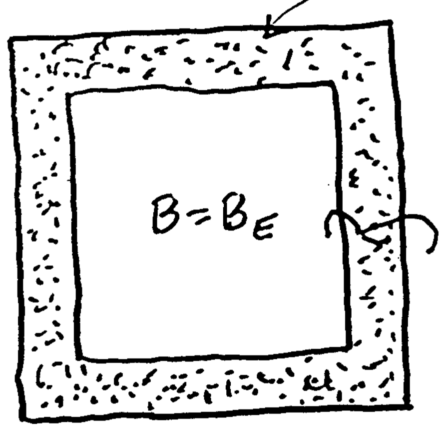
NO TRAPPED FLUX ⇒

NO EXTRA 1/f NOISE

TRAPPED FLUX

FIELD-COOLED

IN SAME FIELD



UNIFORMLY TRAP

FLUX ⇒

A LITTLE EXTR

1/f NOISE

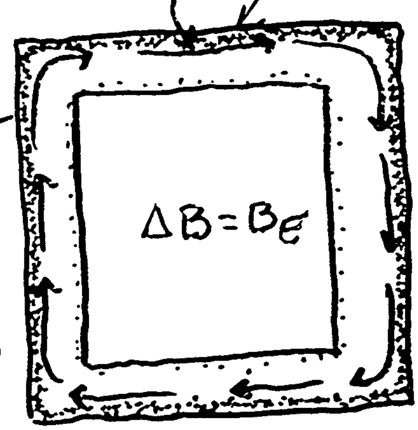
(20 - 100%)

LARGE CURRENT (500 mA)

INJECTED TRAPPED FLUX

ZERO FIELD-COOLED

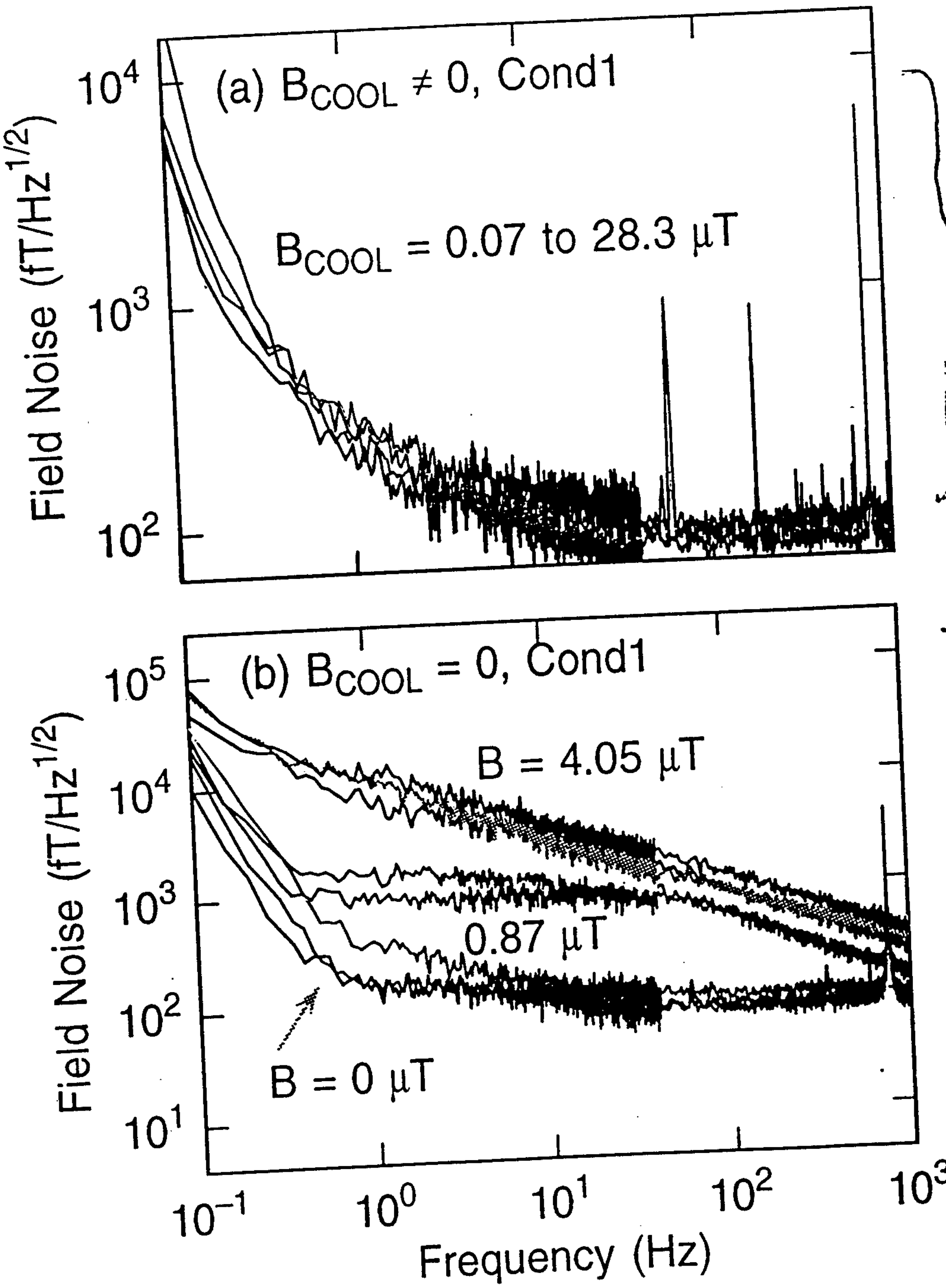
IN A FIELD



CIRCULATING CURRENT LOWER TRAPPING BARR & FLUX RUSHE IN. ⇒

A LOT OF 1/f N

CONDUCTUS IMAG MAGNETOMETER



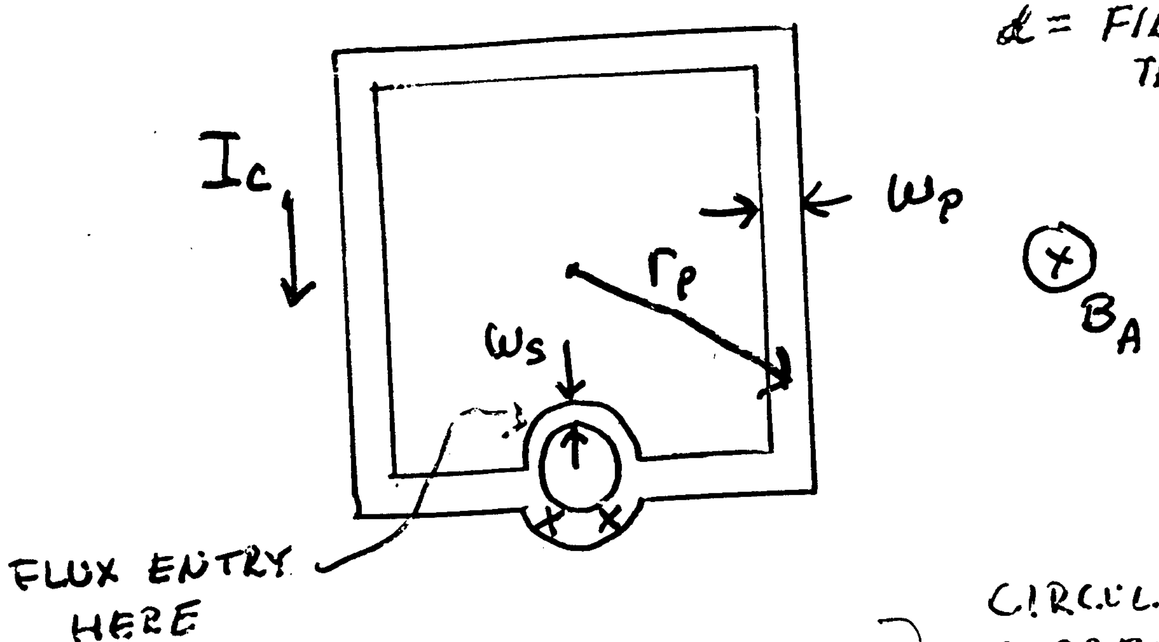
COOL IN DIFF-ERENT FIELDS

CHANGE FIELD WHEN COLD

$B_T \approx 1\ \mu T$

SOURCE OF NOISE WITHOUT FLUXDAM

d = FILM THICKNES



$$I_c \simeq 4 B_A r_p / \pi \mu_0$$ CIRCULATING CURRENT FROM B_A

$$I_T \equiv (J_c d w_s) \left[2.5 \left(\frac{\Phi_0 / w_s^2}{10^{-6} J_c d} \right)^{1/4} \right]$$ MAX I_x BEFORE FLUX ENTRY

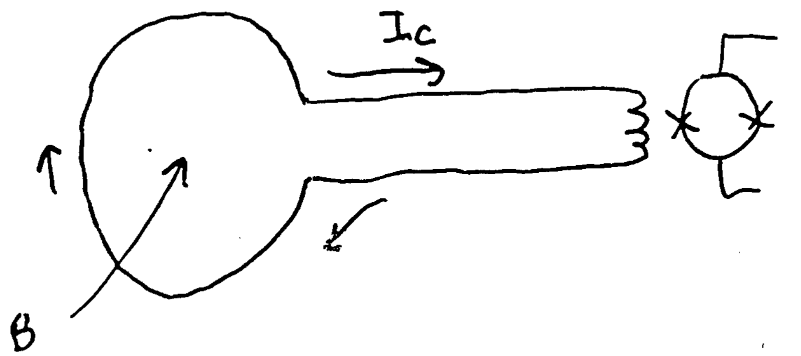
$$I_T \simeq \sqrt{w_s}$$

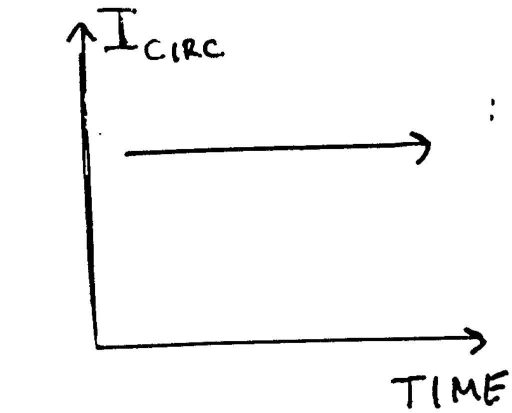
$$\boxed{B_T \approx 1 \mu T}$$

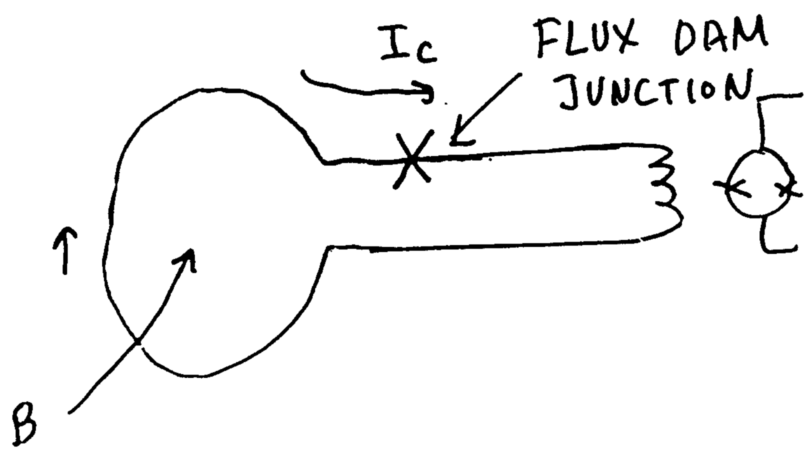
DESIGN RULE

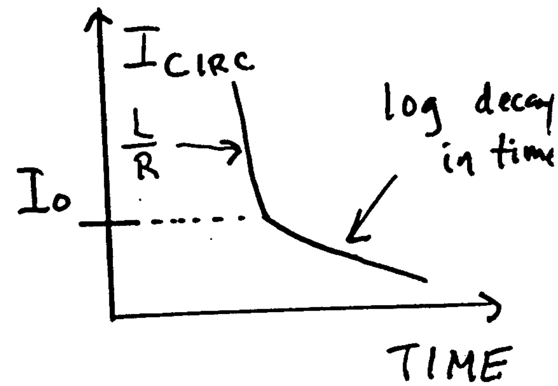
IF $I_0^{F.D.} < I_T$ AVOIDS THIS PROBLEM

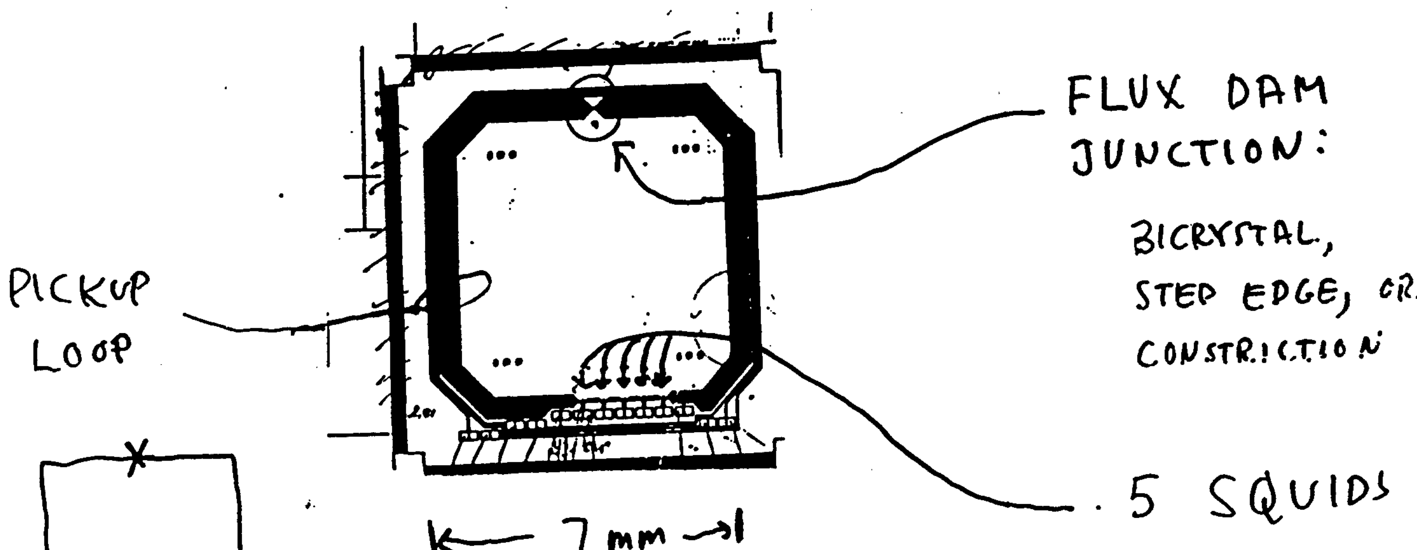
HOW TO AVOID PERSISTENT CIRCULATING CURRENTS

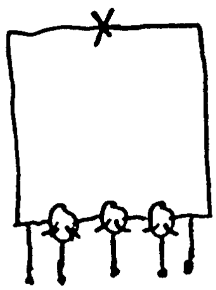




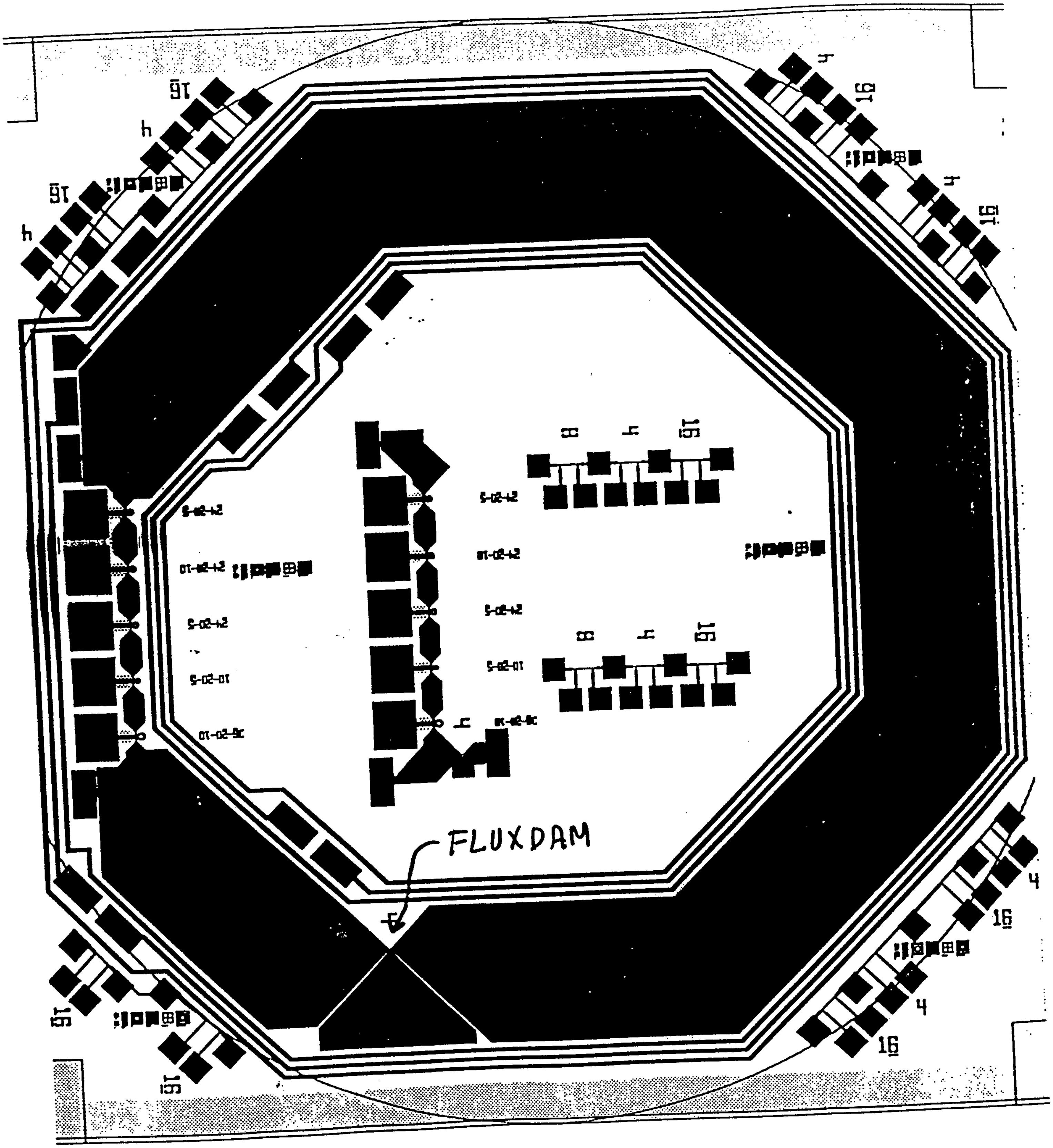








STEP EDGE 1x1 CM MAGNETOMETER

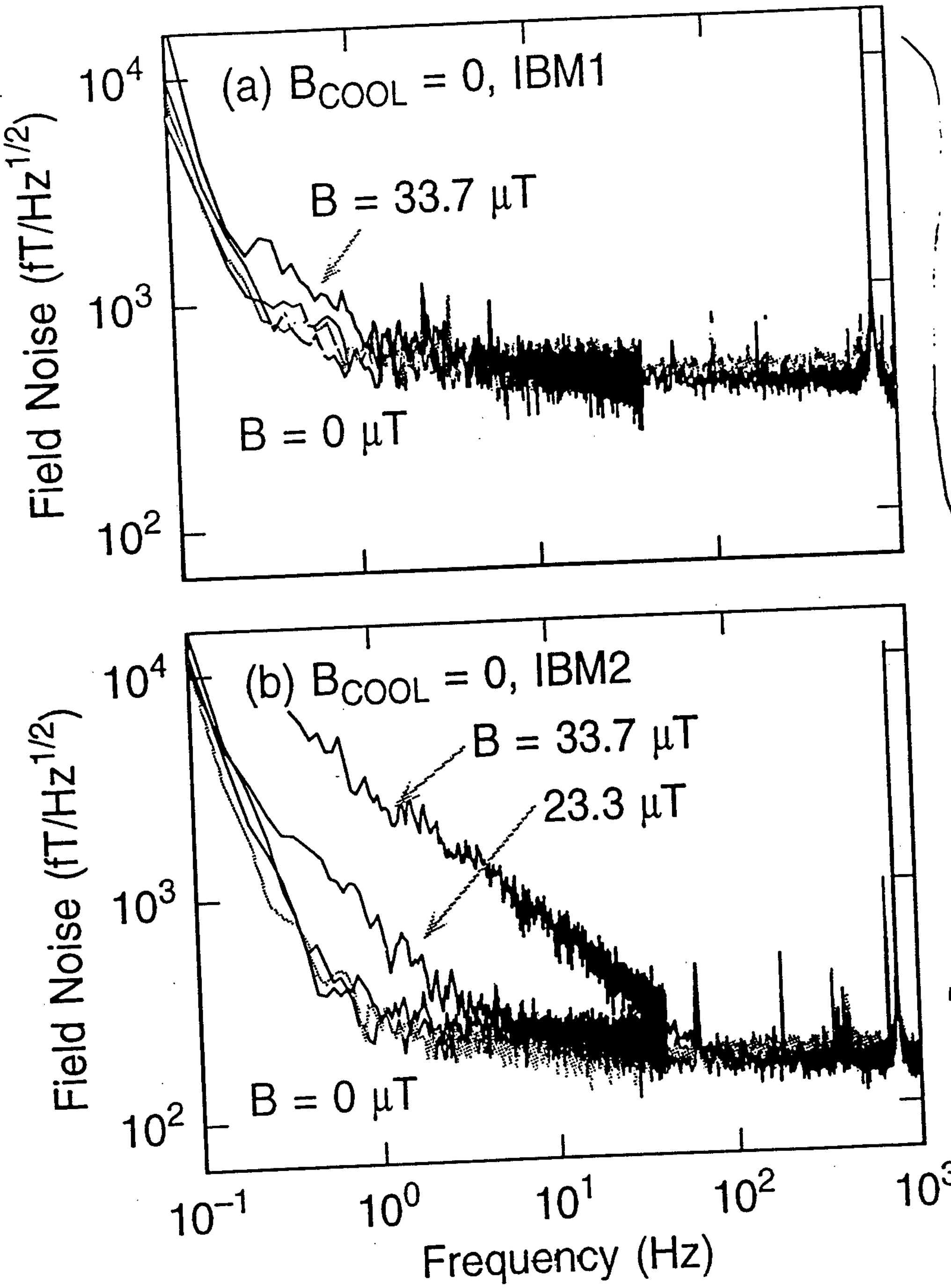


R.H.Koch 06/18/97 20:18:21

u-ps (7.1 10 Mar 1995): -center -replace -color -for R.H.Koch fmf3.ugh

IBM SQUIDS WITH FLUXDAMS:

1x1 cm D.C. MAGNETOMETERS

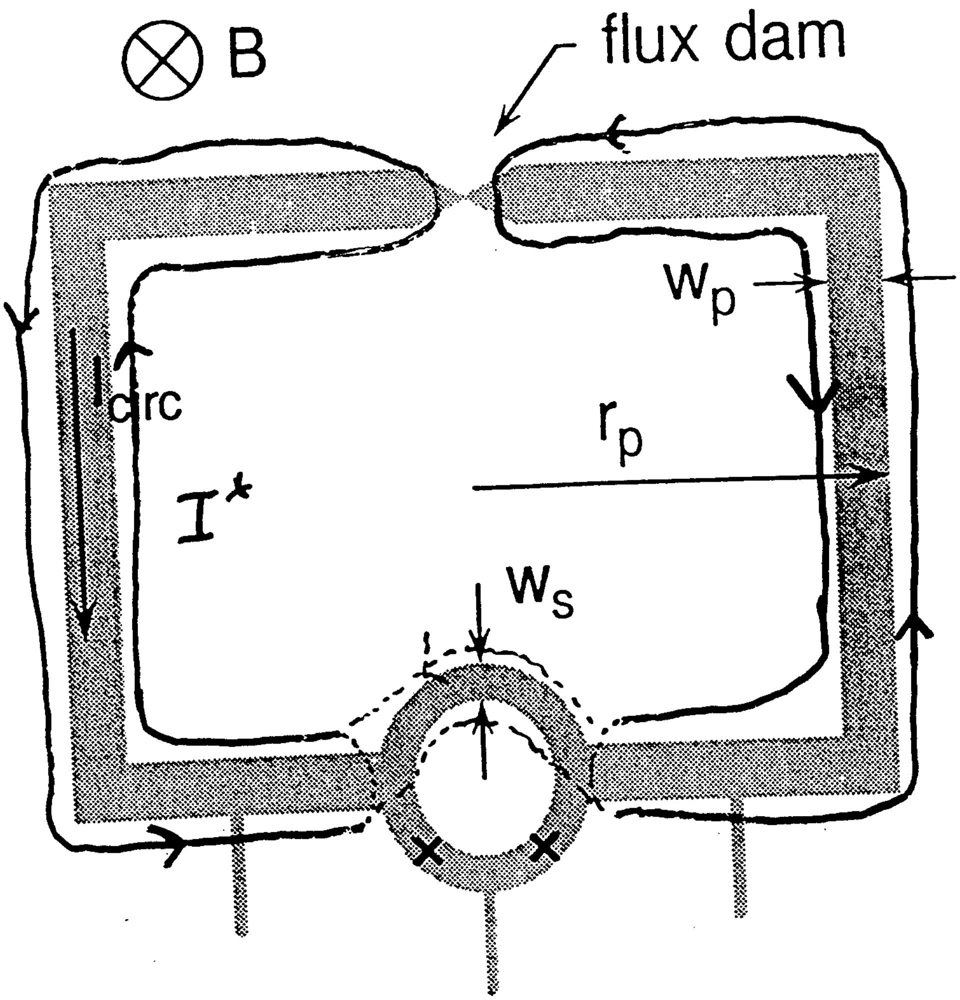


$B_{COOL} = 0$

CHANGE FIELD WHEN COLD

NOISE FROM CURRENTS AROUND THE PICKUP LOOP FILMS:

$$I_{circ} \lesssim I_o^{F.D.}$$



$$\boxed{I_T < I_o^{F.D.}}$$

DESIGN R[...]

$$I^* = 4 B w_p / 4 \mu_o$$

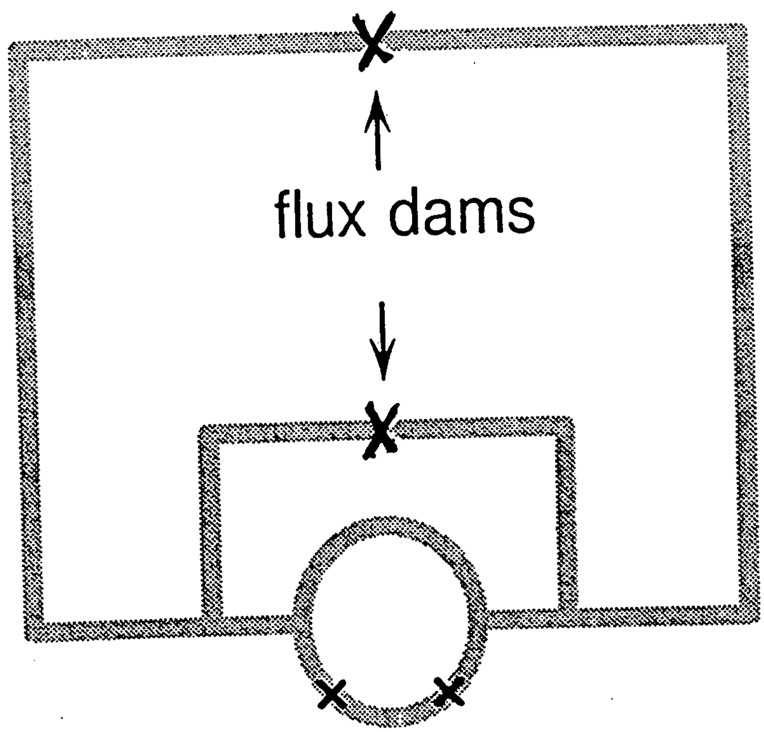
$$I_T^* \cong (J_c d w_p)\left[2.5\left(\frac{\Phi_o / w_p^2}{10^{-6} J_c d}\right)^{1/4}\right]$$

$$\boxed{B_T^* \simeq 27 \mu T}$$

SOLUTIONS TO I^* NOISE:

1) ω_p SMALL $\Rightarrow$ L_p BIG $\Rightarrow$ POOR RESPONSE

2) ADD A SECOND LOOP:



"DUAL FLUXDAMS"

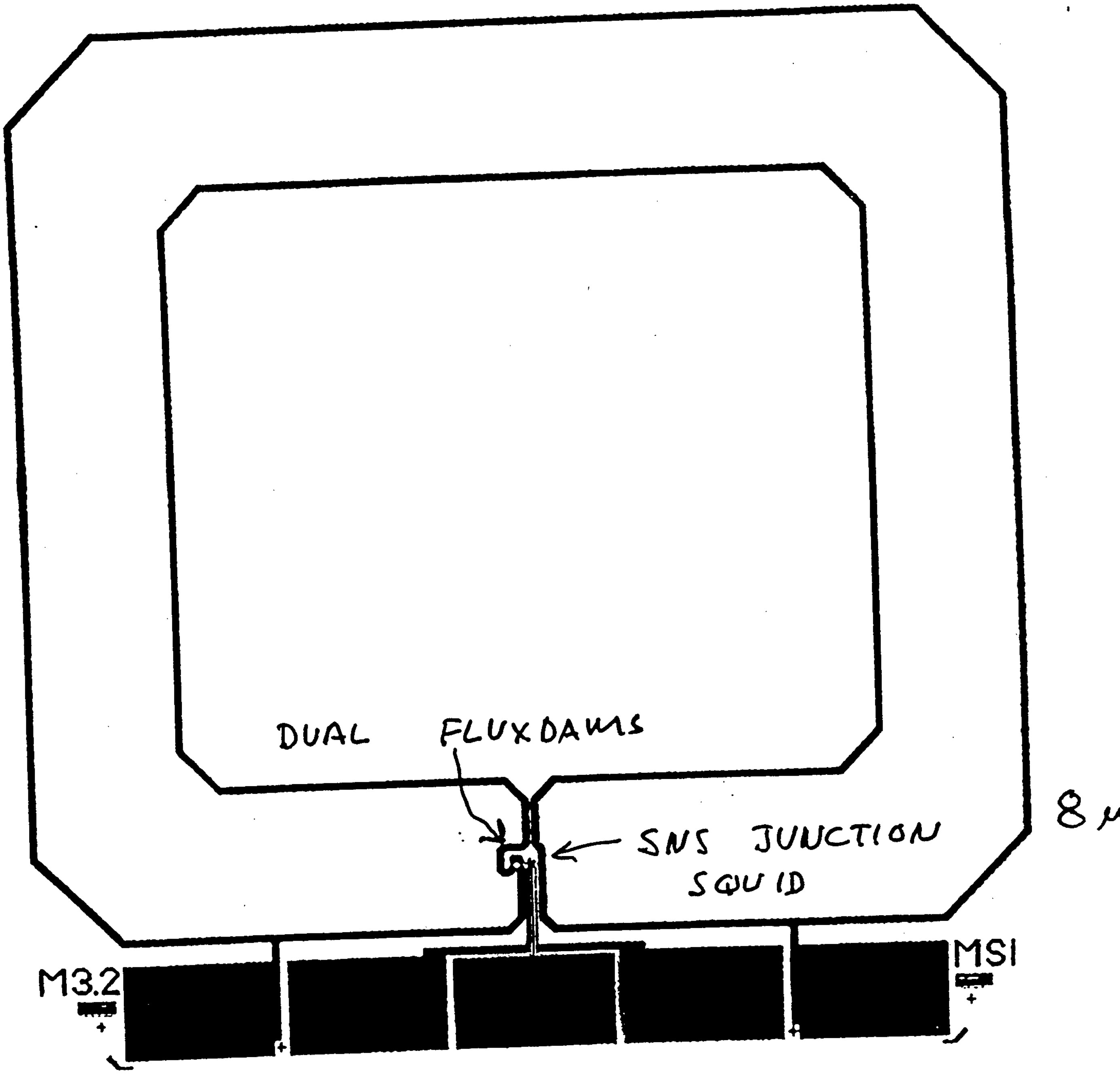
MAKE ω_p SMALL SO THAT:

$$I^*_{\text{FROM EARTH FIELD}} \ll I^*_T$$

TWO FLUXDAM SQUID MAGNETOMETER

14×14 mm substrate
2 flux dams
100 μm linewidth
2 mm "washer" width

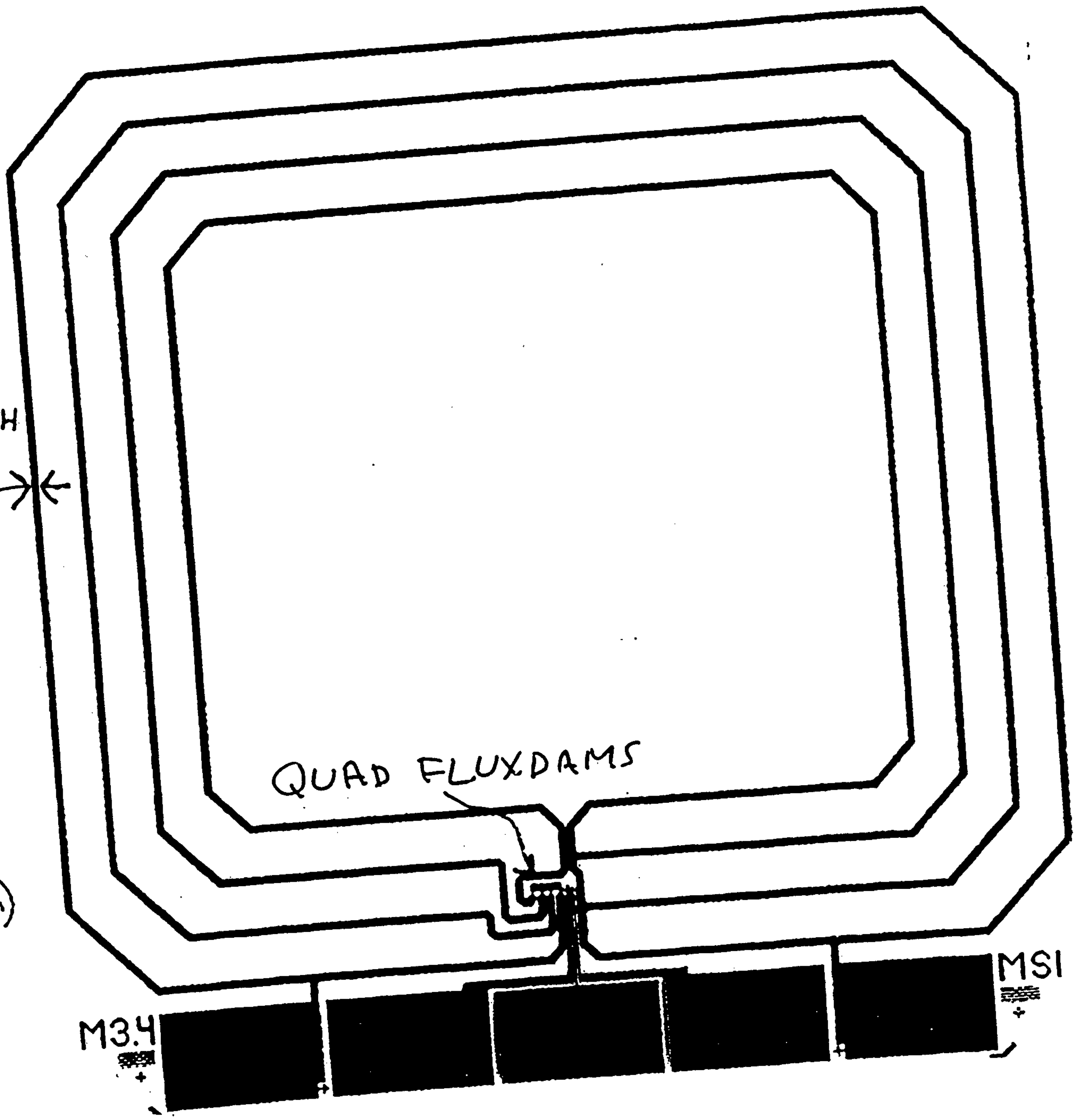
i.e. A/A, SUBSTR.
$30/50



FABRICATED BY MAGNESENSORS (SAN DIEGO)
FOR IBM
WITH DAN LATHROP (QM)

FOUR FLUXDAM SQUID MAGNETOMETER

100 µm
LINEWIDTH

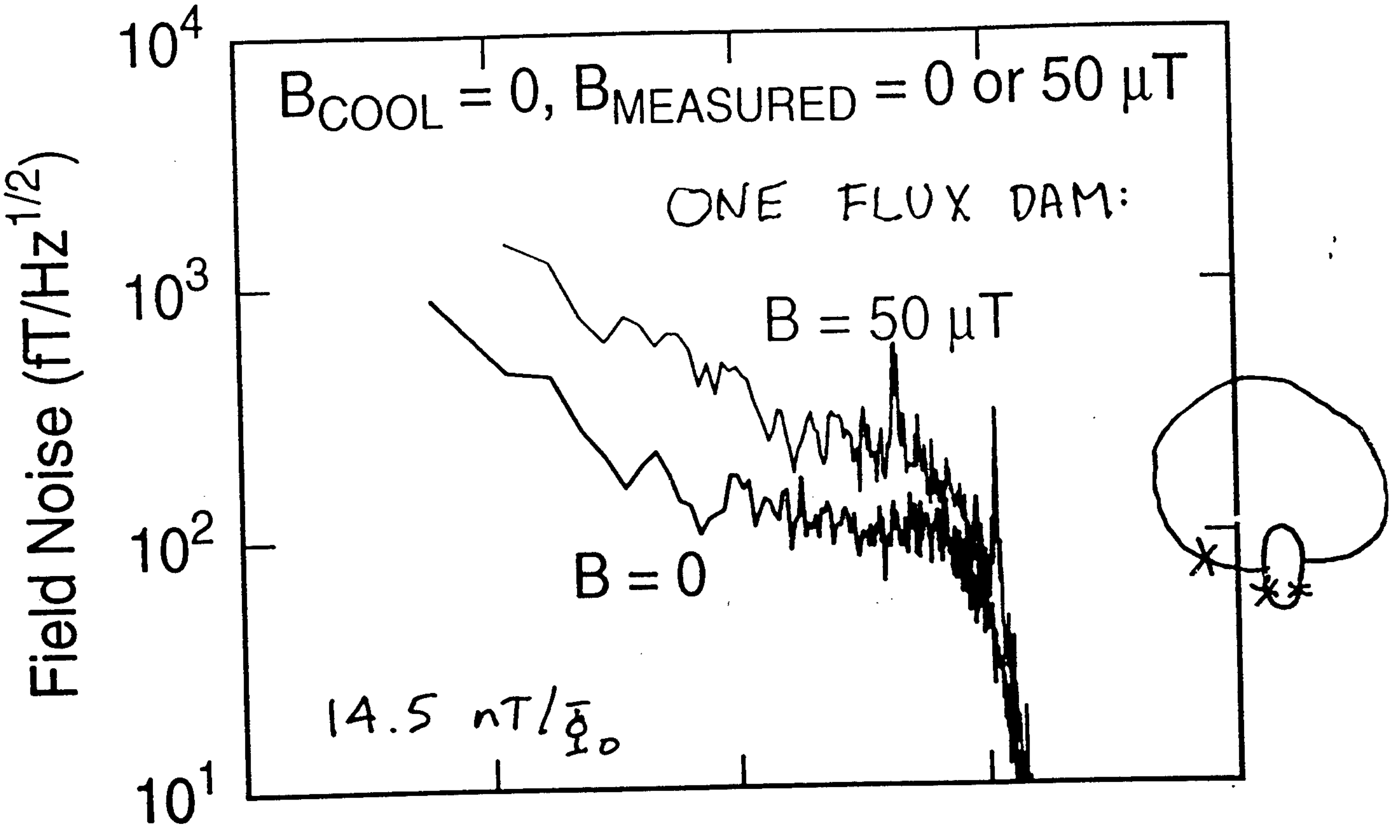


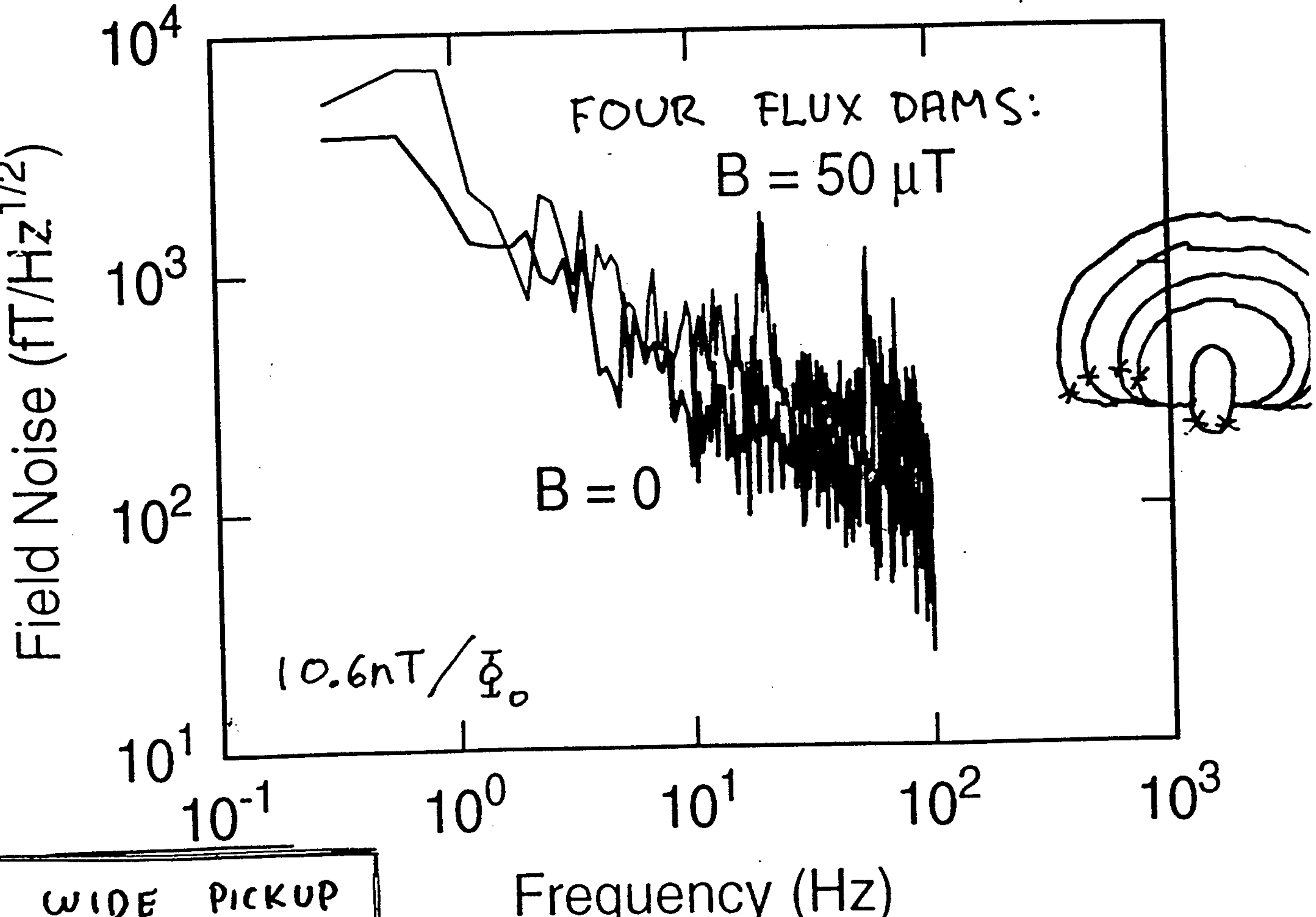
4x14 mm substrate

10 µm linewidth

.mm from outer line
to inner line
(= "washer" width)

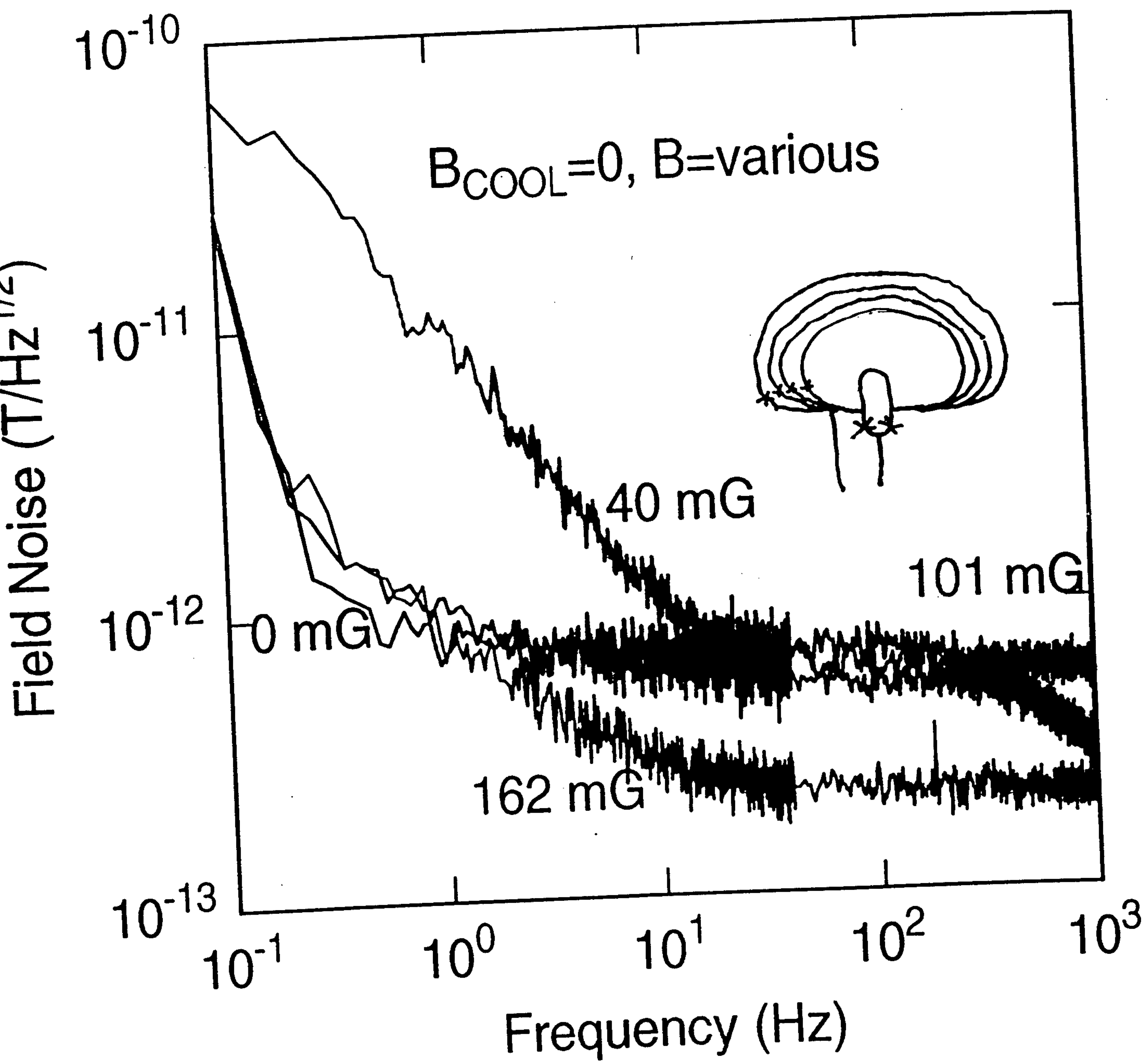
FABRICATED BY MAGNESENSORS (SAN DIEGO)
FOR IBM
WITH DAN LATHROP (QM)





ONE WIDE PICKUP LOOP $\Rightarrow$ $7nT/\Phi_0$

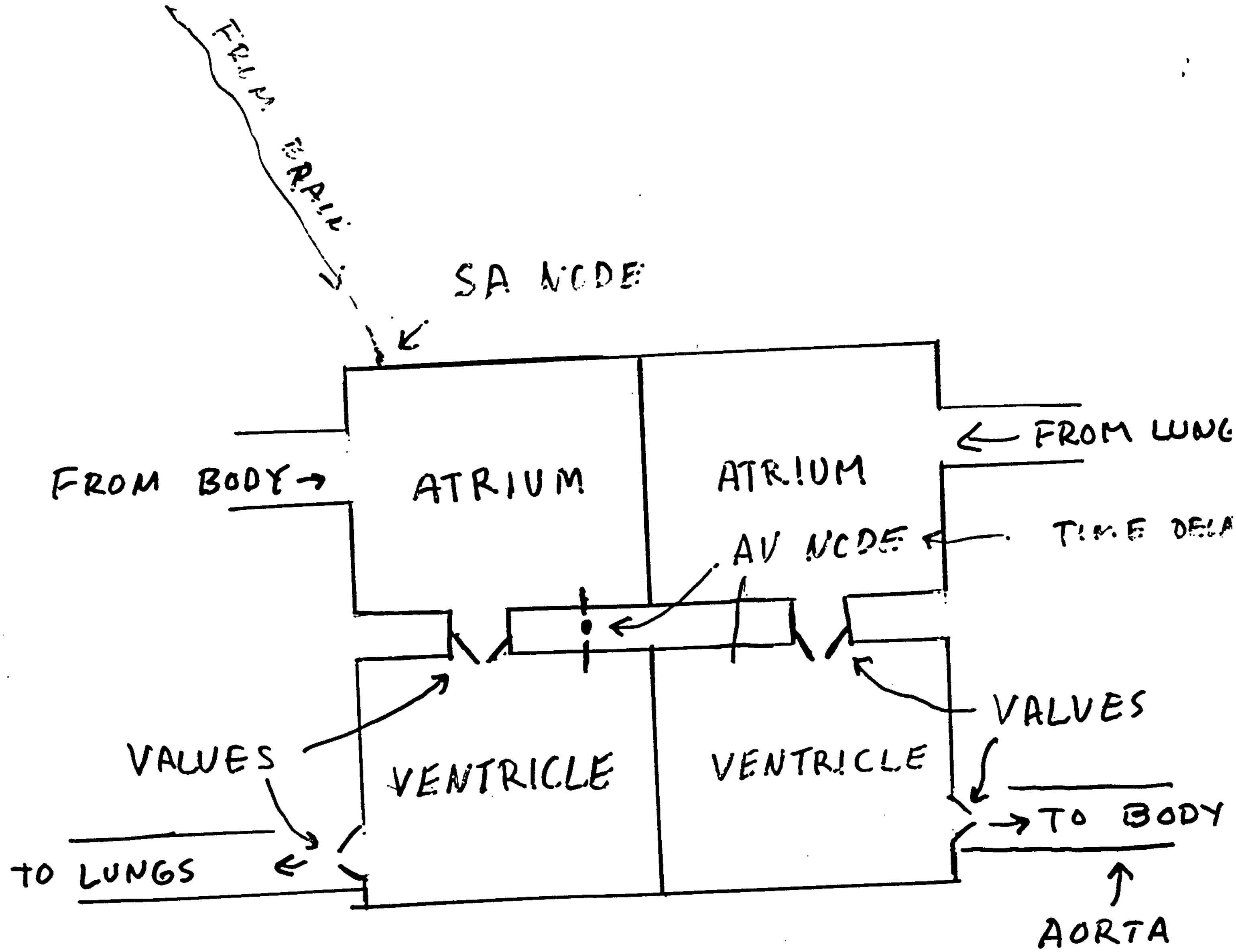
ANOTHER FOUR FLUXDAM SQUID:

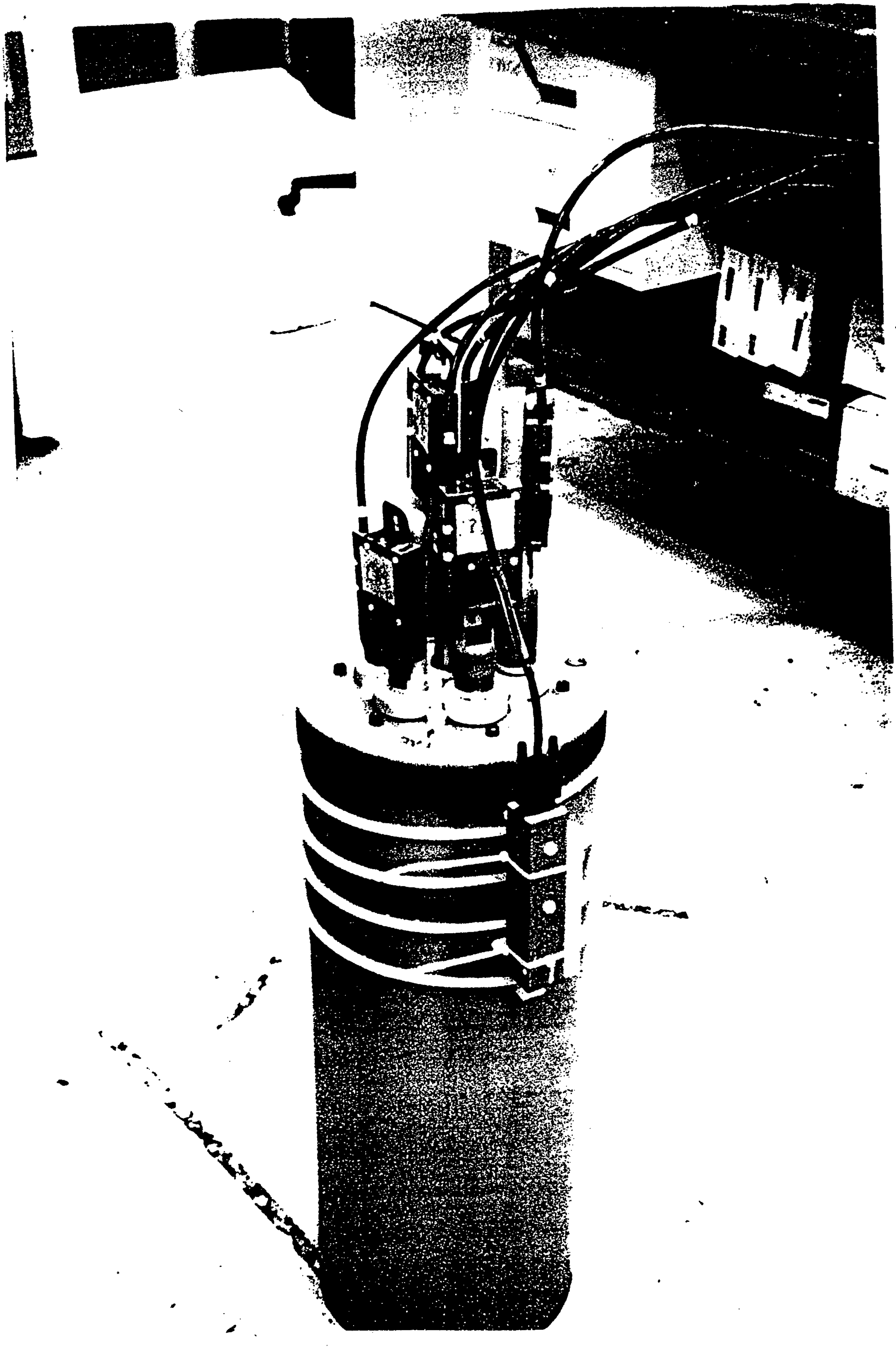


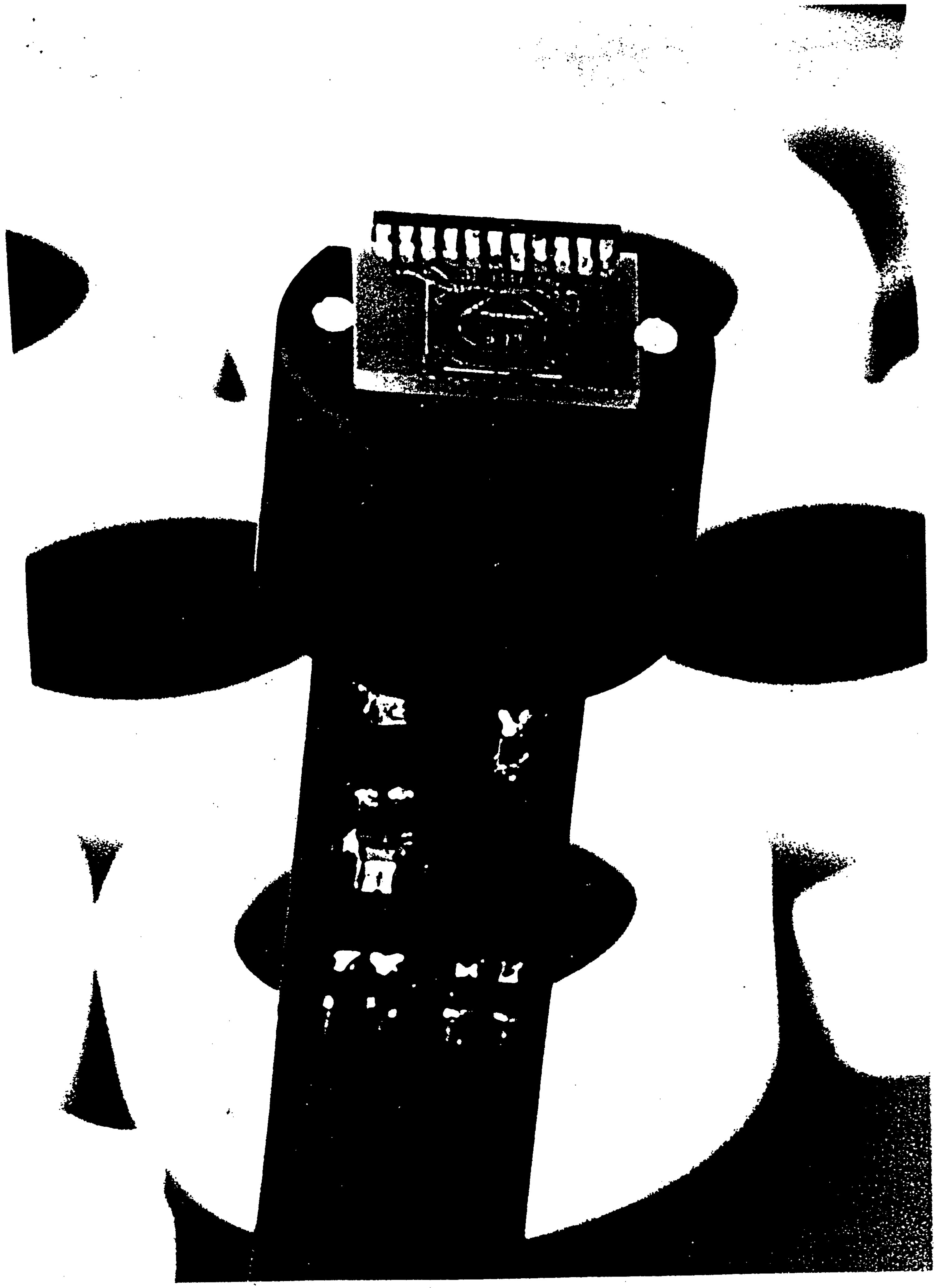
OPERATING WITHOUT BIAS REVERSING

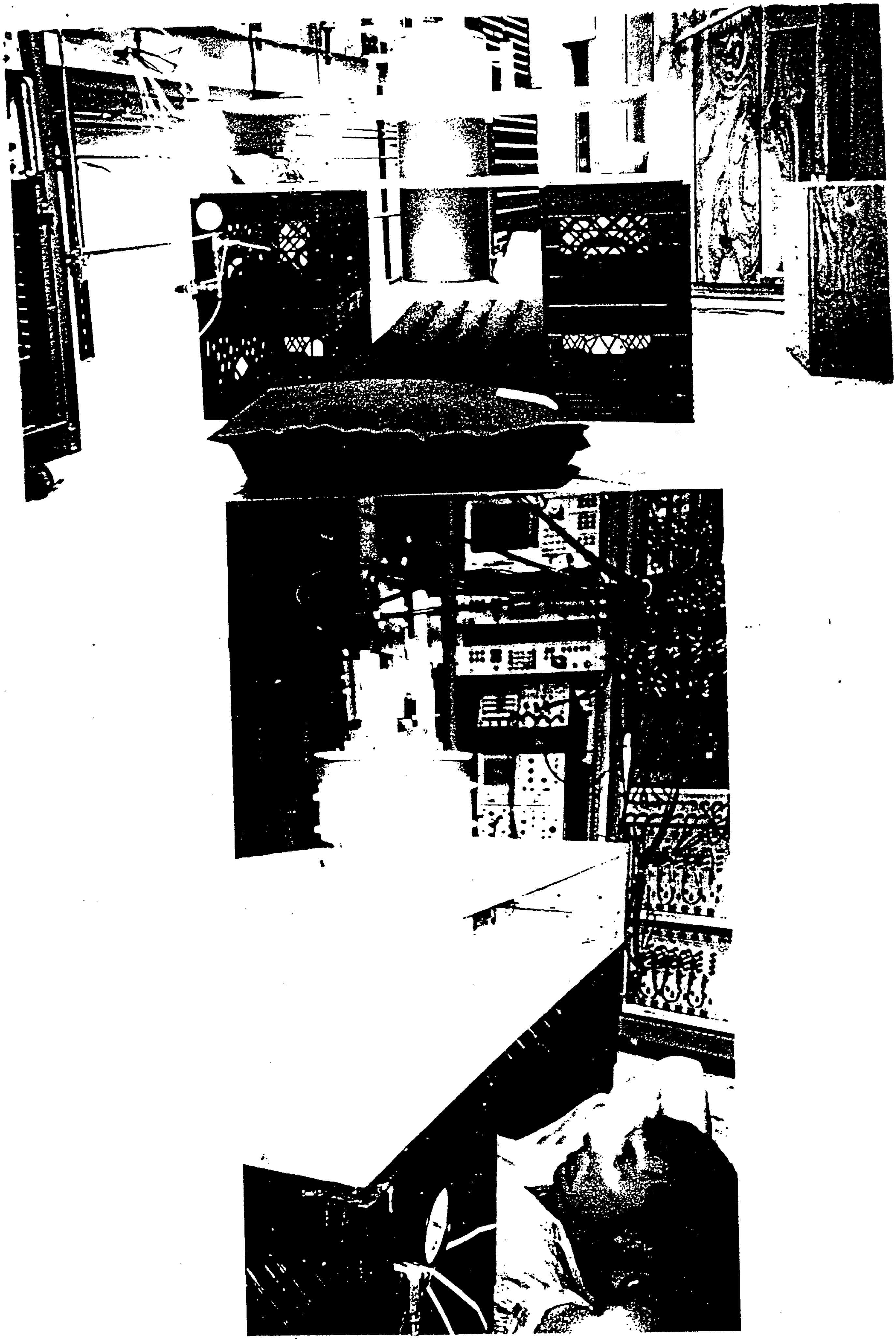
BIOMAGNETISM

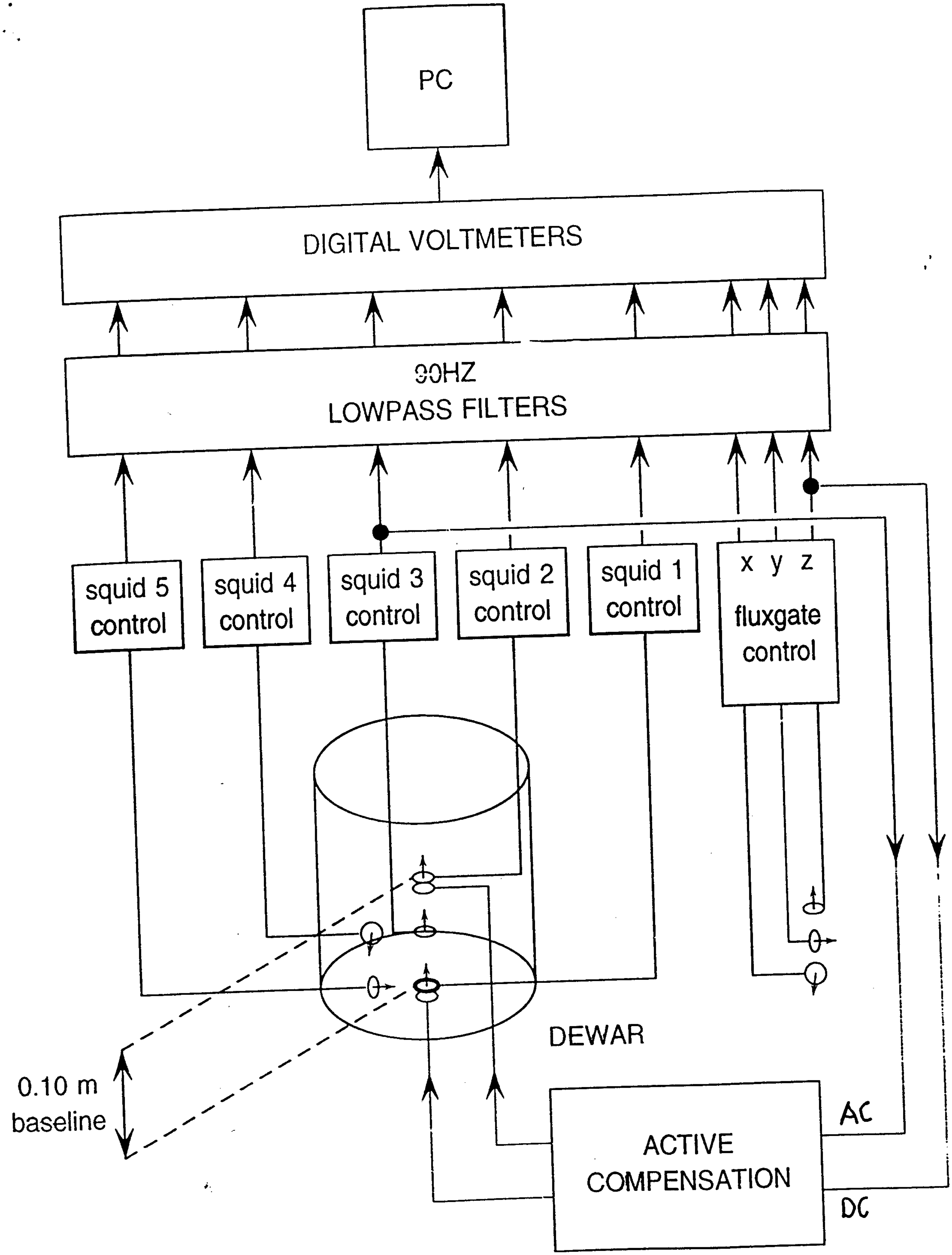
THE HEART AS A PUMP





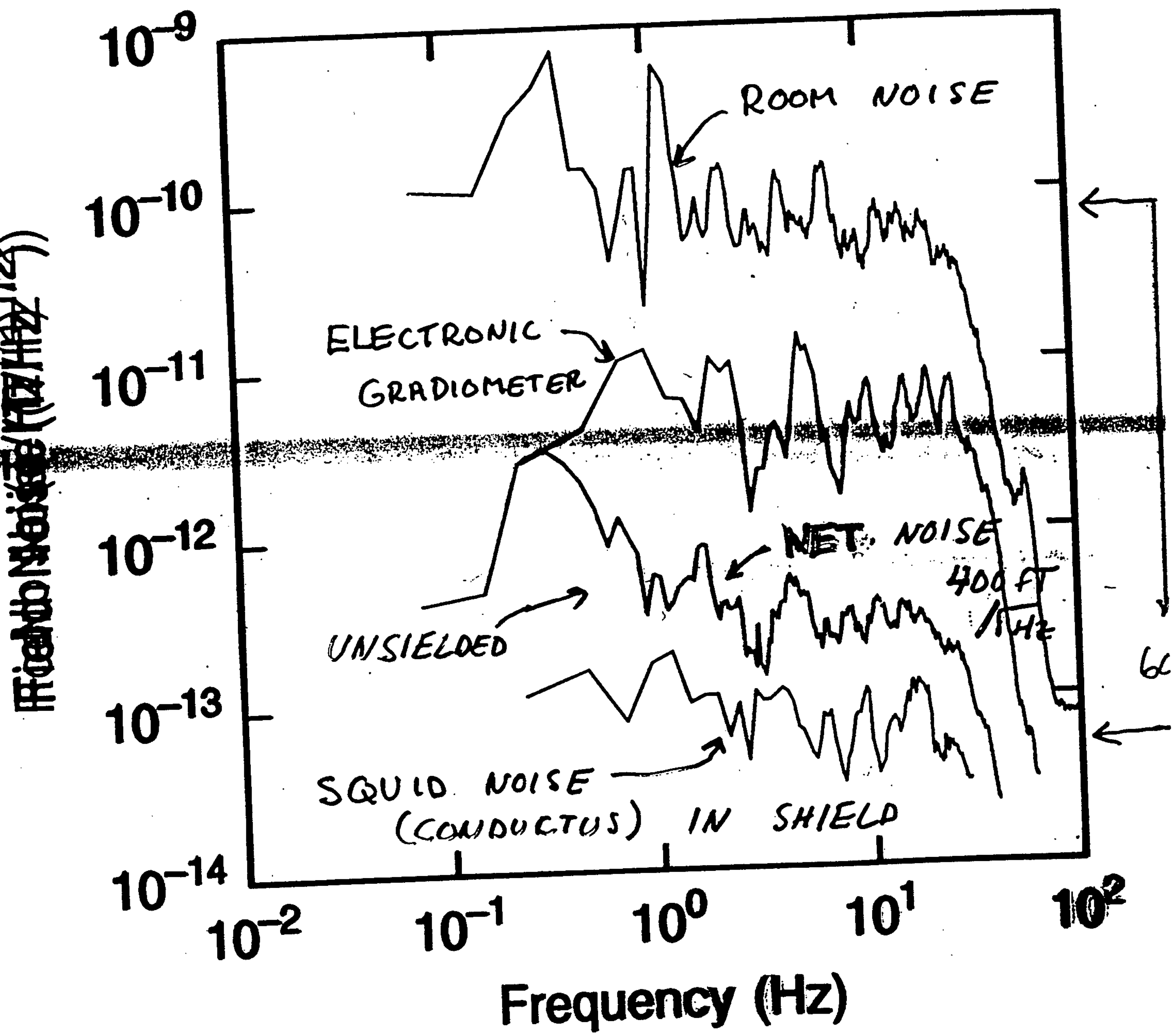


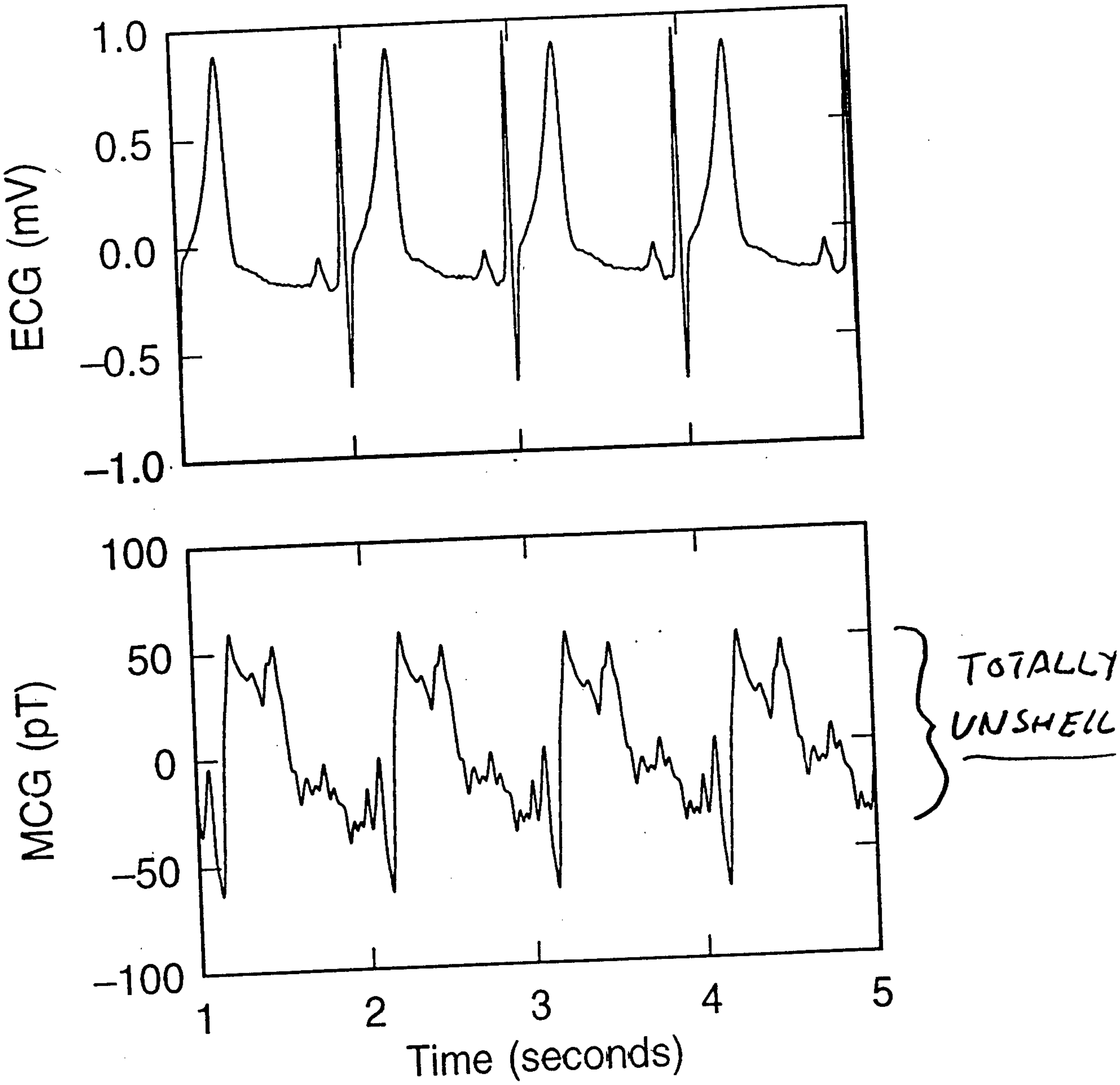




User: WOELT1 Host: WOELT1 Job: <untitled> Date: 8/24/1996 Time: 13:39 Queue: W12000BC Printer: W12000B4

UNSHIELDED BIOMAGNETOMETER:




1.0
0.5
0.0
–0.5
–1.0
ECG (mV)
100
50
0
–50
–100
MCG (pT)
1
2
3
4
5
Time (seconds)
TOTALLY
UNSHELL

ECONOMIC ISSUES IN SQUIDERY:

Making (just) SQUIDs is a money losing operation today.

- Compare: Conductus (SQUIDs) with Billingsley Magnetics (fluxgates)
- SQUIDs are very high tech and hard to make
- SQUIDs are a "part"
- Most SQUID markets are too small to support the research that is needed to develop the SQUID part of the solution. (-> government money)
- Need cheaper SQUID technology

Making systems that use SQUIDs can make money.

- Look at Quantum Design, biomag companies, and IBM
- The SQUID is a key part but a minor cost item in most systems.
- Cost to enter a new market is far more than that of the SQUID sensors
- Risk is very high since products are new and different.
- There are just a few cases of market pull, usually its technology push.

SQUIDs (and superconductivity) have far more intellectual (and snob) appeal than other types of magnetic sensors, i.e. Fluxgates.

WHAT COULD CHANGE ALL THIS DOOM AND GLOOM?

(small scale) High-Tc needs to become a part of some major research and/or commercialization area (as defined by Dow Jones):

Electronics, computers, communications, and information

Aerospace and transportation

Biophysics, biochemistry, medical, and drug-related

Energy exploration, production, and distribution

Food

Entertainment

Investment, etc.

Defense

How to find a part in the mainstream?

1. Invent a room temperature superconductor.

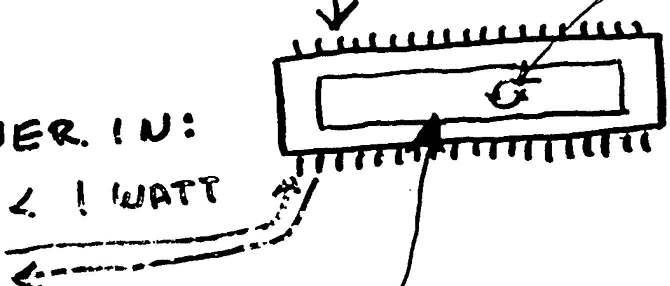
2. Pretend we did:

   Work toward the goal of a micromachined silicon-chip-based refrigerator for high-Tc low-power applications. A small DIP with only electrical power inputs that can cool a high-Tc chip to 77K.

"SILICON MICROMACHINED REFRIGERATOR"

PLUG IN REPLACEMENT FOR A ROOM-TEMPERATURE PART

HIGH-T_c SQUID OR FILTER OR A/D CONVERT OR ...



POWER IN: ~ < 1 WATT

COMPLETE SILICON-BASED CLOSED-CYCLE 77°K COOLER.

PRODUCTION COST IS LINKED TO SILICON

RADIATION LOAD 77° ← 300°K 1x1 cm ~ 0.1 WATTS

CONDUCTION LOAD ≈ 0.2 WATTS

Y. TAVRIN & M. SIEGEL

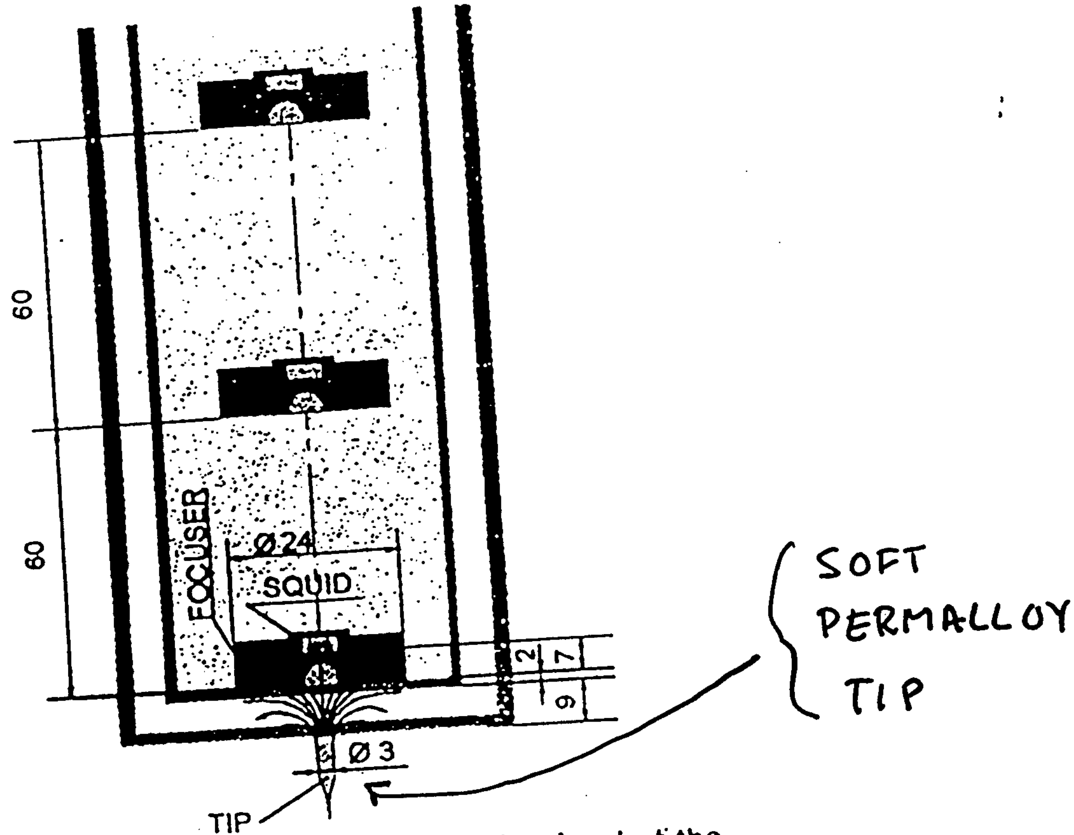
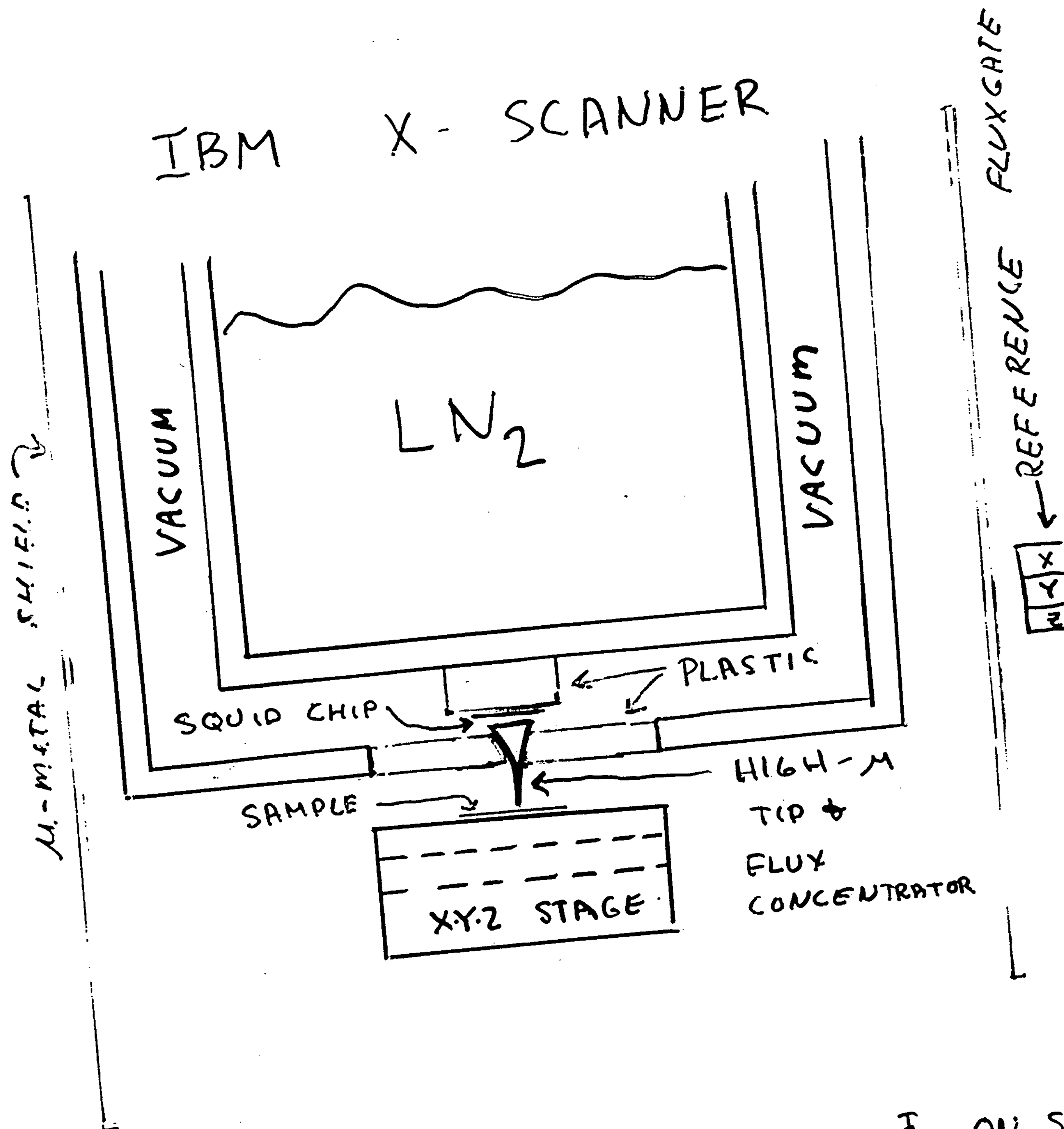


Fig. 1. Schematic view of the measuring head of the HTS SQUID microscope showing a cut of the cryostat containing the three SQUID sensors with flux focusers forming a second order gradiometer.

HTS SQUID · MICROSCOPE
WITH A FERROMAGNETIC FLUX FOCUSER.

IBM X-SCANNER



1 GAUSS ON SAMPLE $\Rightarrow$ $0.002\ \Phi_0$ ON SQ

SPATIAL RESOLUTION:

EXISTING ~ 5 μm
POSSIBLE ~ 0.1 μm

} TIP SIZE & SHAPE